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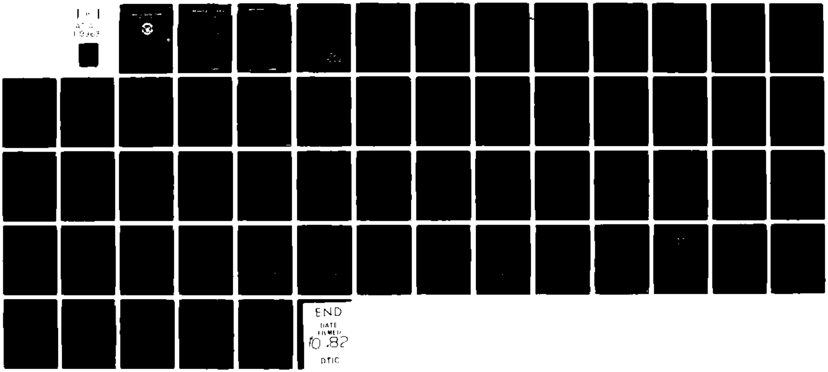

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

THE CONSTRUCTION OF A ND:YAG LASER

by

Jin Won Jung

June 1982

Thesis Advisor: A. W. Cooper

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After a series of the tests, lasing action was observed at the input power of 3.6 kw. The efficiency of the output power to input was found to be 0.04% (slope) or 0.008% overall, approximately 20% of the values for a comparable commercial laser. The low laser efficiency is ascribed to low cavity pumping efficiency and inadequate cooling. Recommendations are made for improvement of system performance.

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The Construction of a Nd:YAG Laser

by

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Lieutenant Colonel, Korean Army
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ABSTRACT

A neodymium laser was constructed with a locally designed circular cylindrical pumping cavity. Laser action was achieved under conditions predicted.

A Nd:YAG crystal was selected for use in the laser, and the physical and chemical properties of Nd:YAG as compiled from the literature are presented. The theoretical and experimental approach for designing the Nd:YAG laser system, and a detailed description of the laser system are given, with the expected operational characteristics extrapolated from measurements on a commercial laser.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure

I. INTRODUCTION

This thesis work is related to the construction of a Nd:YAG laser for studying atmospheric transmission properties, which was done by O'Harrow [1] in 1972 for the purpose of analyzing atmospheric transmission over Monterey Bay.

Generally, the Nd:YAG laser is the most commonly used type of solid state laser at the present time having several merits relative to other solid state lasers. The 1.06 μm radiation characteristic of neodynium is in the near infrared and lies in a very transparent portion of the atmosphere. Detectors for this wavelength are relatively simple and inexpensive. Also neodynium lasers can be operated in a continuous wave mode at sufficiently high output powers to insure a meaningful range. And the cubic structure of YAG favors a narrow threshold for laser operation.

The homemade double-elliptical pump cavity built in 1972 was checked relative to the commercial K-Y2 (KORAD) system. It was found that the fluorescence generated in the homemade cavity was less than half of that in the K-Y2, at the threshold input power condition.

Empirical data shows that small elliptical cavities with small ratio of major axis to rod diameter are more efficient than large cavities in several respects, such as

the fraction of direct radiation and singly reflected radiation absorbed, and the probability of lost radiation being redirected to the rod.

Actually, the homemade double-elliptical pump cavity is about three times as big as the commercial laser system, K-Y2, with the same size of laser rod, and the same tungsten lamps and cooling system. The method used to shape the ellipse of the homemade cavity was very crude and the surface of the cavity is also crude with several dots and scracthes, which resulted in lower efficiencies of focusing and reflectivity than expected. For the above reasons, it was found necessary to make a new pumping cavity for further operation of the laser.

In order to avoid the machining difficulties of the elliptical shape which could not be overcome in the local machine shop and to compensate for the low reflectivity of the cavity wall, a circular-cylindrical pumping cavity with four 1000 watts lamps was made by the Physics Department machine shop and used for this thesis work. While it was realized that the efficiency of this cavity would be low, the large increase in pump power was expected to allow the lasing threshold to be achieved. It was also recognized that the high input power with low efficiency would require additional cooling capacity.

The fluorescent emission from each rod was monitored as a function of pumping powers using the same geometry in each case. The PIN-10 detector was mounted in each se to detect the total emission of fluorescent radiatio filtered at 1.06 μm, emitted axially from the end of laser rod.

II. PROPERTIES OF Nd:YAG CRYSTALS

Over the past several years, a great deal of research has been accomplished in the development of solid state laser materials and systems. Among the most thoroughly studied has been the neodymium laser emitting radiation at 1.06 μm through a variety of host materials. The primary host materials studied have been glass and yttrium aluminum garnet(YAG) and it is known that neodymium doped yttrium aluminum garnet (Nd:YAG) possesses a combination of properties uniquely favorable for high power laser operation. Although other crystalline materials have been tried as the host material, glass and YAG have certain characteristics which make them much better for high repetition rate, Q-switched laser systems.

A. PHYSICAL AND CHEMICAL PROPERTIES OF Nd:YAG

The YAG structure is stable from the lowest temperatures up to its melting point and no transformations have been reported in the solid phase. The strength and hardness of YAG are lower than Ruby but still high enough that normal fabrication procedures do not produce any serious breakage problems. Pure $Y_3Al_5O_2$ is a colorless, optically isotropic crystal which posseses a cubic structure

TABLE I

PHYSICAL AND CHEMICAL PROPERTIES OF Nd:YAG

Chemical Formula	$Y_3Al_5O_{12}$:Nd
Crystal Structure	
Symmetry	Cubic
Space group	O_h^{10}-I_a3d
Lattice constant	12.01 Angstroms
Melting point	1970°C
Hardness	
MOHS scale	8.5
Vickers (111)	1548
Specific gravity	$4.56 \pm .04$
Water absorption	Zero
Solubility	
Water	Insoluble
Common acids	Slightly
Thermal expansion coefficient (0-250°C)	
(100) Orientation	8.2×10^{-6} °C^{-1}
(110) Orientation	7.7×10^{-6} °C^{-1}
(111) Orientation	7.8×10^{-6} °C^{-1}
Thermal conductivity	
20°C	0.0320 cal/sec-°C-cm
40°C	0.0290
100°C	0.0250
200°C	0.0225

TABLE I (Contd)

Specific heat capacity (0-20°C) -----	0.141 cal/gm-°C
Modulus of elasticity ---------------	0.45×10^{6} lb/in^{2}
Tensile strength --------------------	$25\text{-}30\times10^{3}$ lb/in^{2}
Poisson ratio ----------------------	0.3 (est)
Refractive index --------------------	1.82±.003
Output polarization -----------------	Unpolarized
Brewster's angle -------------------	61.2°
Critical angle ----------------------	33.3°
Normal dopant level Nd^{3+} ------------	0.7% by weight
Stimulated emission cross section ---	$2.7\text{-}8.8\times10^{-19}$ cm^{2}
Relaxation time ($^4I_{11/2}$ - $^4I_{9/2}$) ----	30 ns
Radiative lifetime ($^4F_{3/2}$ - $^4I_{11/2}$) -	550 μs
Spontaneous fluorescence lifetime ---	230 μs
Scatter losses ----------------------	0.002 cm^{-1}
Photon energy at 1.06 μm ------------	1.86×10^{-19} J

characteristic of garnets. The YAG host is hard, of good optical quality, and has a high thermal conductivity.

In Nd:YAG, trivalent neodymium substitutes for trivalent yttrium, so charge compensation is not required. And there is practically no competition for the Nd^{3+}. The radii of the two rare earth ions differ by about 3%. Therefore, with the addition of large amounts of neodymium, strained crystals are obtained - indicating that either the solubility limit of neodymium is exceeded or that the lattice of YAG is seriously distorted by the inclusion of neodymium. Some of the important physical and chemical properties of YAG are listed in Table 1.

Figure 1 and 2 are graphs showing some of the optical properties as functions of temperature. The values given in the table and graphs were collected from various references cited in the bibliography.

B. ENERGY LEVELS OF TRIVALENT NEODYMIUM

The Nd:YAG laser is a four-level system as depicted by an energy level diagram in Figure 3. [2]. The laser transition, having a wavelength of 10641 Å, originates from the $^4F_{3/2}$ level and terminates at the $^4I_{11/2}$ level. The decay processes from the higher energy band to the $^4F_{3/2}$ state are fast, nonradiative transitions. At room temperature only 40% of the $^4F_{3/2}$ population is at level R_2; the remaining 60% is at the lower sublevel R_1 according

to Boltzmann's law. Lasing takes place only by R_2 ions whereby the R_2 level population is replenished from the R_1 by thermal transition. The upper laser level, $^4F_{3/2}$, has a flourescence efficiency greater than 99.5% [3], and a radiative lifetime of 230 μsec. [4]. The branching ratio of emission from $^4F_{3/2}$ is as follows; [5]

$^4F_{3/2}$ --- $^4I_{9/2}$ = 0.25, $^4F_{3/2}$ --- $^4I_{11/2}$ = 0.60,

$^4F_{3/2}$ --- $^4I_{13/2}$ = 0.14, $^4F_{3/2}$ --- $^4I_{15/2}$ < 0.01.

This means that almost all the ions transferred from the ground level to the pump bands end up at the upper laser level, and 60% of the ions at the upper laser level cause flourescence output at the $^4I_{11/2}$ manifold. The ground level of Nd:YAG is the $^4I_{9/2}$ level. The relaxation of the $^4I_{11/2}$ state to the ground state, $^4I_{9/2}$, is fast enough to allow the crystal to support continuous wave lasing action at room temperature. This is the most important advantage of neodymium over ruby and other three-level systems where the lasing transition takes place to the ground state.

Figure 4 [6] shows the fluorescence spectrum of Nd^{3+} in YAG near the region of the laser output with the corresponding energy levels for the various transition.

The absorption of Nd:YAG in the range of 0.3 to 0.9 μm is given in Figure 5. [7].

C. FLUORESCENCE PROPERTIES OF Nd:YAG

For design optimization of a solid state laser system it is important to know particular properties of the crystal's fluorescence. They are the fluorescence lifetime and the fluorescence conversion efficiency under optical exitation.

1. Fluorescence Lifetime

The fluorescence decay of Nd:YAG from the $^4F_{3/2}$ energy level to the $^4I_{11/2}$ level is almost independent of temperature in the range 300-500°K. The average fluorescence lifetime as determined by Thorton, et al., [8] in this temperature range was 228 ± 15 μsec. The accepted value quoted in most other sources is around 240 μsec. The fluorescence lifetime is a strong function of the neodymium doping level as presented in Figure 6.

2. Fluorescence Conversion Efficiency

The excitation energy for a laser system usually extends over a broad spectral range, and it is worthwhile to know how effectively the laser material converts the absorbed pumplight into fluorescence.

The 1.06 μm relative fluorescence conversion efficiency at 300°K as a function of excitation wavelength is presented in Figure 7 [9]. This curve is temperature

dependent in the temperature range 300-500^{o}K. Although not shown in Figure 7, the peaks at 0.52 μm and 0.59 μm increase significantly with temperature and become dominant over those in the infrared at approximately 475^{o}K. The peaks located in the infrared portion of the curve are essentially temperature independent.

III. CONSIDERATION OF DESIGN OF THE LASER SYSTEM

In construction of a pump cavity, several critical design areas can be identified; these are efficient cooling of laser rod, lamps and reflector; design of the various O-ring seals; the selection of the reflector base material, polishing and plating procedures, and prevention of arcing.

The mechanical design of a cavity is determined mainly by two considerations; the geometry chosen for efficient energy transfer from the pump source to the laser material, and the provisions required for extracting the heat generated by the pump source.

A. REFLECTOR BASE MATERIAL

The metals most commonly employed to obtain specular reflecting surfaces in laser cavities are Aluminum, Silver and Gold. The reflective metal surfaces are usually obtained by evaporation, sputtering, polishing, or electroplating. Commonly used base materials are copper and aluminum. Copper has almost double the thermal conductivity and lower thermal expansion compared to aluminum, but it is much more expensive and heavier.

The reflectivities of metal surfaces are wavelength dependent. For CW-pumped Nd:YAG laser, where most of

the pumping occurs in the wavelength region between 0.7 and 0.9 μm, gold is used almost exclusively. The reflectance versus wavelength of materials is shown in Figure 8. [10].

B. PUMP SOURCE

For the CW operation of Nd:YAG, the majority of systems employ either Krypton-filled arc lamps or Tungsten-halogen filament lamps. The krypton arc lamp has an 800 W/cm electrical input with 15kw maximum input per lamp, while the standard tungsten filament lamp has an 275 W/cm electrical input and 1.5kw maximum input per lamp.

The output of a krypton-arc lamp as a radiated efficiency over the range 0.3 μm - 1.2 μm of 61 percent and an intense line output at 0.81 μm which is efficiently abosrbed by neodymium-doped laser hosts. [11]. The tungsten lamp emits only 30 percent of its energy at wavelengths shorter than 1 μm. [12].

Typical overall efficiencies obtainable in krypton-pumped Nd:YAG lasers are between 2 and 3 percent, while that of the tungsten lamp is 1 to 1.5 percent. [13]. Krypton-arc pumped Nd:YAG lasers have currently the highest power, but for lower power applications, tungsten lamps have the advantage of simplicity and low cost. The emphirical relative performances of krypton and tungsten-iodine lamps are given in Figure 9. [14].

C. GEOMETRY OF THE PUMPING CAVITY

The experimental work carried out on pump cavity design shows that a single elliptical cylinder and a spherical cavity are the best for maximum efficiency and relatively short laser rod, up to 10 cm in length. The double elliptical cavity is less efficient but it is widely used at the present time.

Small elliptical cavities with low major axis to rod diameter ratio are more efficient that large cavities. In a small elliptical cavity the fraction of direct radiation is high, and most of the pump radiation is incident on the rod after a single reflection on the cavity walls. Another strong argument for making elliptical cavities as small as possible is the increased probability of the lost radiation being redirected to the laser rod if the ratio of the cavity volume to laser rod volume is small.

D. LASER ROD

Commercially available laser crystals are grown exclusively by the Czochraeski method. At the present time, rods can be fabricated with maximum diameter of about 10mm and length of up to 150 mm.

Neodymium concentration by atom percent in YAG has been limited to 1.0 to 1.5%. Higher doping levels tend to shorten the fluorescent lifetime, broaden the line-width, and cause strain in the crystal, resulting in poor

optical quality. In specifying Nd:YAG rods, the emphasis is on size, dimensional tolerance, doping level, and passive tests of rod quality. For CW operation a low doping concentration from 0.6 to 0.8% [15] is usually chosen to obtain good beam quality.

E. COOLING

There are two basic cooling methods, water cooling and forced air cooling. The primary purpose of the liquid is to remove the heat generated in the laser rod, pump source, and laser cavity. Sometimes the coolant serves as a filter to remove undesirable pump radiation. 10% of Potassium Dichormate solution is used to filter out the blue and near-ultra-violet radiation, since there is evidence that these wavelengths can produce color centers (solarization) and increase the CW threshold level in some YAG crystals. [16].

The temperature increase of the coolant as it passes through the laser cavity is given by $T = Q/C_p.m$ where Q is the extracted heat, C_p is the specific heat of the coolant, and m is the mass flow rate.

Forced air is sometimes used to cool the laser rod and flash lamp in low average power lasers. For standard air (20° C, 1 atm) we obtain

$$f_v = \frac{48 \times P(W)}{\Delta T(^\circ C)} \text{ ltr/min} \qquad [17]$$

where f_v is the airflow, ΔT is the temperature difference between inlet air and exhausted air and P is the heat extraction. If 300 to 600 ltr/min of airflow at a static pressure of 30 torr and 16°C temperature difference is applied, the heat removed ranges from 100 - 200 watts.

IV. CONSTRUCTION OF THE LASER

The laser system has three major subsystems consisting of the optical pumping cavity, laser rod and cavity cooling systems, and optical resonator. The other systems used are Variac power supply, detectors, and heat removal fan. Figure 10 shows general view of the laser system.

A. OPTICAL PUMPING CAVITY AND LASER ROD

The cavity geometry is a circular cylindrical cavity with four lamps. The rod is aligned parallel to the cylindrical axis at center. Figure 11 is a detailed drawing of the cavity. The cavity was machined from a solid block of aluminum by drilling out the core and was then hand polished. The inside surface of the cavity was finished by machine drilling and so it is quite crude. The end plates in Figure 12 were made from 5/16 inch aluminum plates with 5 holes for heat removal by air convection. Optical pumping of the rod is accomplished with four tungsten-iodide, quartz-envelope lamps placed at a certain distance for diffusive focusing. The lamps used are manufactured by General Electric, mfg stock no. Q1000T3/4CL with a rated output of 1000 watts at 120 volts. Figure 14 shows the details of the lamp mounting assembly.

The Nd:YAG laser rod used has the following dimensions: it is cylindrical in shape with a diameter of 3mm and length of 75mm. The ends are cut plane parallel with an anti-reflection coating for 1.06 μm. Two rods of identical specifications were purchased; one from Crystal Optics Research Inc., and the other from the Airtron Division of Litton Industries.

B. OPTICAL PUMPING CAVITY AND LASER ROD COOLING SYSTEM

Since the pump cavity is designed to use 4000 watts of input power, both liquid cooling and air-flow cooling methods are adopted for removing heat efficiently. The liquid cooling system is the K-WC3 laser cooler which was originally designed for the K-Y2 Nd:YAG laser (KORAD) with cooling capacity of 1800 watts, and its recommended operating flow rate is 2 - 2.2 GPM. This K-WC3 employs a deionizer to maintain the low electrical conductivity necessary for water in the laser head.

The cooling water goes to the laser rod first which is enclosed in a 1cm diameter pyrex glass tube and flows through 12 holes serially connected in the cavity block. The flow rate was 2 GPM and the initial inlet water temperature was 20°C and outlet water temperature was 25°C. After 9 minutes operation with 4400 watts of input power the inlet water temperature was 28°C and the outlet water temperature was 34°C.

Figure 13 displays the details of the laser rod mounting and cooling assembly.

A high speed fan (model No. B7A81C-2DR: Eastern Air Devices Inc.) which has a 100 CFM capacity at 3300 RPM at 0.6 ampere and 120 volts was installed on a tripod about 1 feet high in order to cool mainly the lamps.

Forced air cooling with 100 CFM was identified to be sufficient for this Nd:YAG laser system by showing that about half of the total heat can be removed.

The temperature inside the cavity was measured with a thermocouple with digital reading (Doric Scientific. Model 403A). The temperature inside the cavity measured with the fan operating and without the fan is given in Figure 15.

The temperature increase in the cavity was linearly dependent on increase of the input power. Temperature measurement without the fan was recommended to be done only below 2000 watts of input power because of the possibility of lamp breakage. Temperature measurement with fan was limited at 1100°C inside cavity, corresponding to 2800 watts of input power, because the insulation cover on the thermo-couple began to burn.

The heat extracted by forced air convection, calculated by the formula; $f_v = 49xP(W)/\Delta T(^oC)$, was about 1300 watts where ΔT is 23°C, and input power was 2800 watts. The

temperature measurement of the outlet air was a little crude because of sensitivity to position of the thermocouple and so a low temperature difference was used in calculation. No temperature measuring device was installed at the rod inlet making it impossible to determine the exact thermal gradient along the length of the rod.

C. OPTICAL RESONATOR

The optical resonator consisted of two, one inch diameter mirrors, one flat and the other spherically curved with a radius of curvature of 1.5 meters. The flat mirror was dielectric coated on one side for 90% reflectance and coated on the other side for maximum transmission. The curved surface of the spherical mirror was coated for maximum reflection. These mirrors were purchased from Valpey Corp., and according to spectophotometer recordings supplied by the manufacturer, the coatings are effective over a narrow bandwidth of about 100 Å centered at 1.06 μm.

The mirrors were mounted in two inch diameter laser mounts using adapter rings. The mounts have orthogonal, micrometer adjustments with an angular resolution of 1 arc second. Longitudinal adjustment can be made by positioning of the adapter rings within the mount.

The confocal mirror configuration gives the smallest possible mode dimension with the mirror separation being

equal to radius of curvature of the mirror. This consists of identical spherical mirrors separated by a distance equal to the radius of curvature. In addition, this arrangement is much easier to align than a flat mirror resonator. The angular adjustment accuracy required is reduced from about 1 arc second to about one quarter degree. [18].

To determine the optimum mirror spacing for a curved, flat mirror resonator, normally referred to as half-confocal, examine the radiation field distribution of a confocal system.

For a confocal resonator the field intensity, perpendicular to the resonator axis, is concentrated near the axis and falls off smoothly away from the axis. In particular, theory shows that for the lowest mode (TEMoo) this lateral distribution is approximately Gaussian. The amplitude is proportional to

$$\exp\left[\frac{-2\pi\rho^2 d}{\lambda(d^2 + 4z^2)}\right] \qquad [19]$$

where ρ is the lateral distance from the axis, and z is the distance from the midpoint. The mirrors are located at $z = \pm d/2$. The amplitude drops by a factor of 1/e in a lateral distance equal to

$$\rho s = \sqrt{\frac{\lambda(d^2 + 4z^2)}{2\pi d}}$$

This is called the spot size. At the center, $z = 0$, the spot size is $\sqrt{\lambda d/2\pi}$, whereas at either mirror, $z = \pm d/2$, the spot size is $\sqrt{\lambda d/\pi}$.

Hence, for the half-confocal resonator the ideal location for the flat mirror is at exactly one-half the radius of curvature of the spherical mirror. To visualize this, place a flat mirror at the midpoint of a confocal resonator (half the radius of curvature); the effect is optically to fold one curved mirror into the other. Therefore the flat mirror receives the maximum intensity from the curved mirror, reducing diffraction losses and alignment problems. For the mirrors used this leads to the resonator length of 75cm used in this project.

V. DETECTOR

There are several good, inexpensive detectors available for use with 1.06 μm radiation.

The detector selected for determining if the lasing threshold was reached was a PIN-10DP photodiode. The PIN-10DP has 1 cm^2 active area and is sealed in a 1 inch O.D. metal housing with BNC output connector. The PIN-10DP is optimized for unbiased operation (photovoltaic) into a current mode op amp, featuring high detector resistance and, thereby, linear light sensing. The relative sensitivity of a PIN-10DP diode to 1.06 μm radiation is approximately 20%. The spectral response of the PIN-10DP is given by Figure 16.

The laser power meter, Model 36-0001; Scientech Inc. was used for measuring laser output. A one inch aperature allows the laser beam to strike the disc calorimeter deep within the body. Its specifications are as follows; spectral response is from 0.25 to 35 microns, power range is from 10 μw to 10 watts, output calibration is 88.4 millivolts per watt, and its accuracy is ± 3%.

VI. ASSEMBLY OF THE LASER

The mirror mounts and laser cavity were mounted to an optical bench consisting of 4 inch aluminum channel stock 5.5 feet in length. The optical bench was mounted on a laboratory table about 42 inches high. The cavity and mirrors were mounted such that the rod and mirror centers would be colinear. The mirrors in precision gimballed mounts were spaced 75cm apart with the cavity 10cm from the flat mirror. This was considered optimum as previously discussed.

The resonator was aligned using a He-Ne laser with focusing lenses installed in front of the laser to direct the beam. A mounting assembly was constructed that would accept either apparatus, adjustable in any direction to facilitate alignment with the rod axis. Once the laser was aligned with the rod axis the mirrors were lined up by superimposing their respective reflections on a common point.

The water cooling system for the rod was connected using 1.3 cm plastic tubing. The lamps were wired in parallel through an ammeter to four General Radio Variacs, Type W10MT3, with a maximum power rating of 1100 watts, 8.5 amps and 130 volts per Variac. Power was supplied to

the Variacs from a conventional wall receptacle located in the laboratory.

For convenience, the rear mirror (spherical mirror) was aligned first, and then the front mirror (flat mirror) was aligned.

VII. OPERATION OF THE LASER

Basically, adequate pumping and precise optical alignment are the key factors to achieve lasing. To determine lasing conditions, two series of tests were made; measurement of the fluorescence, and measurement of laser output power.

A. MEASUREMENT OF FLUORESCENCE

The first series of tests consisted of measuring the fluorescent output as a function of pumping power for the homemade system and comparing the results with those for the K-Y2 laser system. Fluorescence power emitted from a laser medium is a direct measure of the upper laser state population. The fluorescent radiated power emitted from the commercial K-Y2 laser rod at the lasing threshold was taken as an estimate of the required threshold fluorescence for the homemade system, since the two rods are of comparable size and quality. The fluorescent emission from each rod was monitored as a function of input pump power, using the same geometry for each laser pumping cavity. The PIN-10DP detector was mounted in each case to measure the total fluorescent power, filtered at 1.06 μm, emitted axially from the end of the laser rod, as the pumping power was increased. Lasing threshold

pump power was determined for the K-Y2 laser in an independent series of measurements. This threshold fluorescence was found to be 1.75 μw for the K-Y2. With the homemade cylindrical cavity, this power level was attained with an input power of 3600 watts to the pumping lamps. When the maximum available power of 4400 watts was applied the fluorescent power detected reached 2.4 μw, which indicated that the lasing threshold should be achieved. A detailed comparison of the measured fluorescence from the K-Y2 and the homemade laser system is given in Figure 17.

B. MEASUREMENT OF LASER OUTPUT

After several trials of the alignment procedure with the He-Ne laser, lasing output was achieved. With resonator spacing of 75 cm, 0.35 watts of output power was observed at the input power of 4400 watts, which was the maximum available input of this system. This output power agreed with that expected from the comparison of fluorescence between the K-Y2 and the homemade laser system.

When lasing was detected, the overall efficiency of output to input power was very low, about 0.008%. The slope efficiency which is the incremental efficiency as the power is increased above the threshold value is 0.04%. The corresponding efficiencies for the K-Y2 cavity were measured as 0.05% and 0.2% respectively. The output power measurement is given in Figure 18.

C. DISCUSSION

When lasing was detected, the efficiency of the homemade laser system was very low, and the cooling system was found to be inadequate for continuous operation of the system. Also, as the cooling water temperature increased the output power was observed to decrease continuously with time. Due to the time limitation further experimentation to develop an adequate cooling system was suspended.

1. Cooling System

During the operation of the laser system the inlet cooling water temperature was observed to increase rapidly relative to the K-Y2 system operation. The K-Y2 measurements showed thermal stabilization with the K-WC3 closed cycle laser cooler at around 26° for the inlet water temperature, and 29°C for the outlet water temperature at the 2 kw input power. But the homemade laser system with the K-WC3 laser cooler and a high speed fan showed a rapid increase of water temperature from 20°C to 28°C for the inlet water and from about 25°C to 33°C for the outlet water for 9 minutes operation with 4400 watts of input power under the same water flow rate of 2 GPM. The air temperature of the laboratory increased from 23°C to 24°C in this time.

At this point, it is difficult to determine the exact input power overload for the existing cooling system,

but an approximate estimate is about 700 watts, where the water tank capacity is 3 gallons, specific heat of water is 4.18 joule/gm^{o}C, and the temperature increase of the tank water is 8^{o}C for 9 minutes.

In order to meet these amounts of input power overload, two ways could be considered; new design of a water cooling system without fan or only adding a heat transfer unit to the current system, and the implementation of compressed introgen circulation by fan together with the current water cooling system.

2. Laser Output

As mentioned before, it was observed that output power continued to decrease during the operation of the system. The output power decreased from 0.35 watts to 0.25 watts in 9 minutes with 4400 watts of input power. In order to determine the reason of output power decrease several tests were made with changing the input power from 3800 to 4400 watts for short period operation.

Since the cooling system was identified as inadequate for long term operation, it was concluded that thermal effects might cause the problem. Also it is known that the reflectivity of the surface of the pumping cavity decreases, depending on the temperature increase.

Basically, thermal effects in the laser rod are brought about by a combination of heat generation due to absorption of pump radiation and heat flow due to cooling processes. Heating and cooling of the laser material leads to a nonuniform temperature of the rod, which results in a distortion of the laser beam due to the temperature and stress dependent variation of the index of refraction. And so it was estimated that the input power overload due to the insufficient cooling capacity would lead to high thermal gradients in the laser rod, which would lead to optical distortions of the laser beam resulting in thermal defocusing, and an increase of surface temperature inside the pumping cavity.

3. Efficiencies

Even though lasing was detected, the efficiency was very low, and very high threshold power is required. There might be several factors which cause the low efficiency and high threshold; however, discussions were focused on the reflectivity of the pumping cavity surface and the lamps.

Generally, output versus input power calculations can be written: $P_{out} = \sigma_s (P_{in} - P_{th})$ [20], where P_{out} is output power, P_{in} is input power, P_{th} is the lamp input power required to achieve threshold and σ_s is the slope efficiency. The slope efficiency can be simply expressed

as follows: $\sigma_s = n_1 n_2 n_3 n_4 n_5$, where n indicates individual efficiency. The individual efficiency factors are defined as follows: n_1 is the ratio of the absorbed pump power to the fluorescence power of the laser transition; n_2 is the fraction of the electrical input power which results in potentially useful radiation; n_3 is the efficiency obtained in transferring the useful radiation from the pump source to the laser rod; n_4 is the fraction of useful pump light which is actually absorbed by the laser material. This n_4 parameter depends on the doping level and the diameter of the laser rod and on the reflection losses of the pump light on the rod surface; n_5 is the output coupling efficiency, and it can be optimized by proper selection of the output mirror reflectivity. In CW-pumped system the optimum output mirror reflectivity is usually between 80% and 95%, and the output mirror of the homemade laser system was identified as having 90% reflectivity around the lasing wavelength.

The efficiency parameters n_2 and n_3 can be improved by choosing better lamps and better pumping cavity.

Typical overall efficiencies obtainable in Krypton-pumped Nd:YAG lasers are between 2 and 3 percent which are a factor of two better than tungsten lamps, but change of the lamps to Krypton-arc lamps is not practical for the homemade laser system, simply because the Krypton-arc

lamps requires a DC power supply while current tungsten lamps showed enough pumping power and the advantage of simplicity for lower power application.

As mentioned in Chapter IV, the reflectivity of the pumping cavity is assumed to be very low and is considered a major reason for low efficiency. The aluminum material surface with evaporated films or well polished has about 85% reflectivity in the wavelength region between 0.7 and 0.9 μm where most of the pumping occurs and about 90% reflectivity in the wavelength region of the ultraviolet which is detrimental to Nd:YAG laser output, causing solarization in the materials.

The homemade aluminum pumping cavity was machined by drilling and then hand polished. The inside surface of the cavity is quite crude, but it was not possible to measure the roughness of the surface in the absence of an instrument such as profilometer.

At this point, it will be useful to estimate the minimum efficiency of the cavity used. The minimum power required to sustain laser threshold in a rod of volume V can be written approximately as

$$P_{min} = \frac{a_f 4\pi^2 cV(h\nu)}{\lambda^3} \frac{\Delta\nu}{\nu}^{1}$$

where $\Delta\nu/\nu$ is the fractional linewidth of the laser

transition, λ is the transition wavelength, a_f is the gain of the medium, and $h\nu$ is the energy of the metastable state.

The gain of the medium, a_f, can be obtained from the equation, $I = I_0 e^{a_f 2L}$, where L is the length of the laser rod. Assuming that there is a built-in loss of 10% at the transmitting mirror, and there is another 15% loss associated with mirror absorption, diffraction losses, rod imperfections and pyrex tube absorption, we can obtain

$$a_f = \frac{\ln(Io/(0.9)(0.85)Io)}{2 \times 7.5} \ (cm^{-1}) = 0.018 \ cm^{-1}.$$

and then P_{min} for the laser rod used is

$$P_{min} = 0.75 \text{ watts}$$

by assuming that all excitation photons have energy of 1.86×10^{-19} joules (the energy of the $^4F_{3/2}$ state).

However, the coupling of the optical light to the rod is certainly not 100% efficient, and the average energy of an excitation photon from a tungsten lamp is greater than 1.86×10^{-19} joules. Assuming these losses raise P_{min} by a factor of 2, then 1.5 watt is required to sustain threshold.

To finish the calculation, we find the power that would be available to the rod using the following data;

---

[1]Professor A. W. Cooper, Department of Physics, 14 May 1982.

input power of threshold condition is 3600 watts measured from the Homemade cavity, overall efficiency of the tungsten lamps is 1%, and pyrex tube transmission is 88%, and then only 32 watts of optical power is available for absorption if all of it is imaged on the rod. Hence, the minimum efficiency of the pumping cavity used E_{min}, to sustain threshold would be

$$E_{min} = \frac{1.5}{32} \times 100\% = 4.7\%.$$

This efficiency is very low relative to that of the well designed single elliptical cavity which has normally about 30% - 50% efficiency in the small geoemtries with the same size of rod and lamps used in Homemade cavity.

In the calculation of the theoretical value of P_{min}, the coupling of optical power to the rod may be considerably less than supposed. A low efficiency requires an excessive input power resulting in insufficient cooling, decreasing reflectivity of the cavity surface and increasing the internal losses of the rod. If the magnitudes of these losses were known and included in the calculation, P_{min} would increase, and the minimum efficiency of the cavity used would be about double the calculated value, which would give a reasonable comparison with K-Y2 commercial laser system in several respects.

In order to improve the reflectivity of the surface of the pumping cavity, the smoothness of the surface should be improved and the surface of the cavity and the endplates should be coated with gold. The reflectivity of gold is 98% in the wavelength range of 0.7 - 0.9 μm and below 45% in the wavelength range of the ultra-violet region. [21]. Thus, the gold coating would increase the reflection of useful pumping radiation as well as decrease the undesirable ultraviolet reflection, both leading to an improvement over the aluminum cavity reflectivity. Reflective metal surfaces are usually coated by evaporation, sputtering, polishing, or electroplating techniques. Among these methods, evaporated gold is the best method for the homemade pumping cavity.

VIII. CONCLUSIONS

Although lasing was detected with the four lamp circular cylindrical pumping cavity, the lasing threshold was very high and the efficiency was very low relative to that of a normal commercial Nd:YAG laser system.

In the construction of the laser there are several key factors; design of the pumping cavity and selection of base material, resonator placement and reflectivity, design of a cooling system and the selection of the pumping source. It was necessary to make a new circular cylindrical pumping cavity with 4000 watts input power with diffusive focusing as the older double elliptical cavity did not have an adequate pumping efficiency. The pump cavity was designed for optimum size from the consideration of a high fraction of direct radiation and a need for efficient cooling with 12 water holes.

The fluorescence of the homemade pumping cavity showed an almost linear increase with an input power increase and reached the threshold condition as measured for the K-Y2 commercial laser system at 3600 watts of input power.

After a series of tests, 0.35 watts of laser output was detected. It was also determined that the input power at threshold condition is around 3600 watts, as expected.

At this point, the cooling system of the K-WC3 laser cooler and the high speed fan was determined to be inadequate for 4000 watts of input power operation. A series of tests for improving the efficiency of the homemade laser system with a better cooling system is recommended.

Also, it is estimated that gold coating and other improvements to the smoothness of the surface of the pumping cavity and both end plates would increase their reflectivity by up to a factor of two, which is a key factor in getting a lower threshold and better efficiency from the homemade laser system. Otherwise, a small single or double elliptical pumping cavity of which efficiency is much better than the homemade cavity, is recommended to be purchased from the outside for better operation with the current cooling system, being considered to be adequate for this purpose.

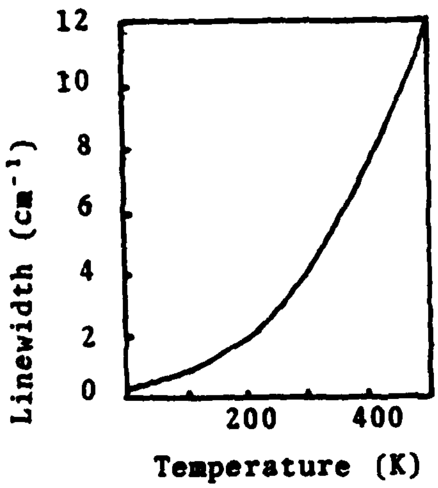


Fig. 1. Linewidth of Nd:YAG 106 μm fluorescent line with Temperature

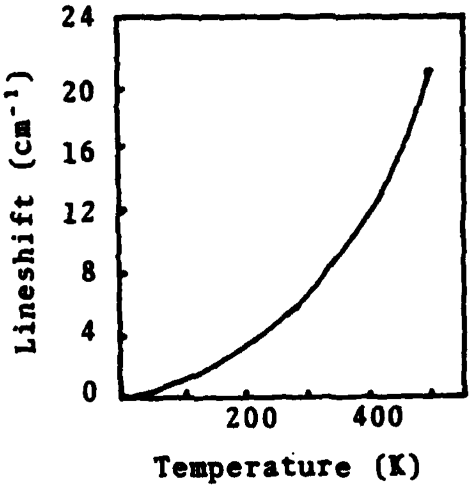


Fig. 2. Lineshift of a Nd:YAG 1.06 μm fluorescent line with Temperature

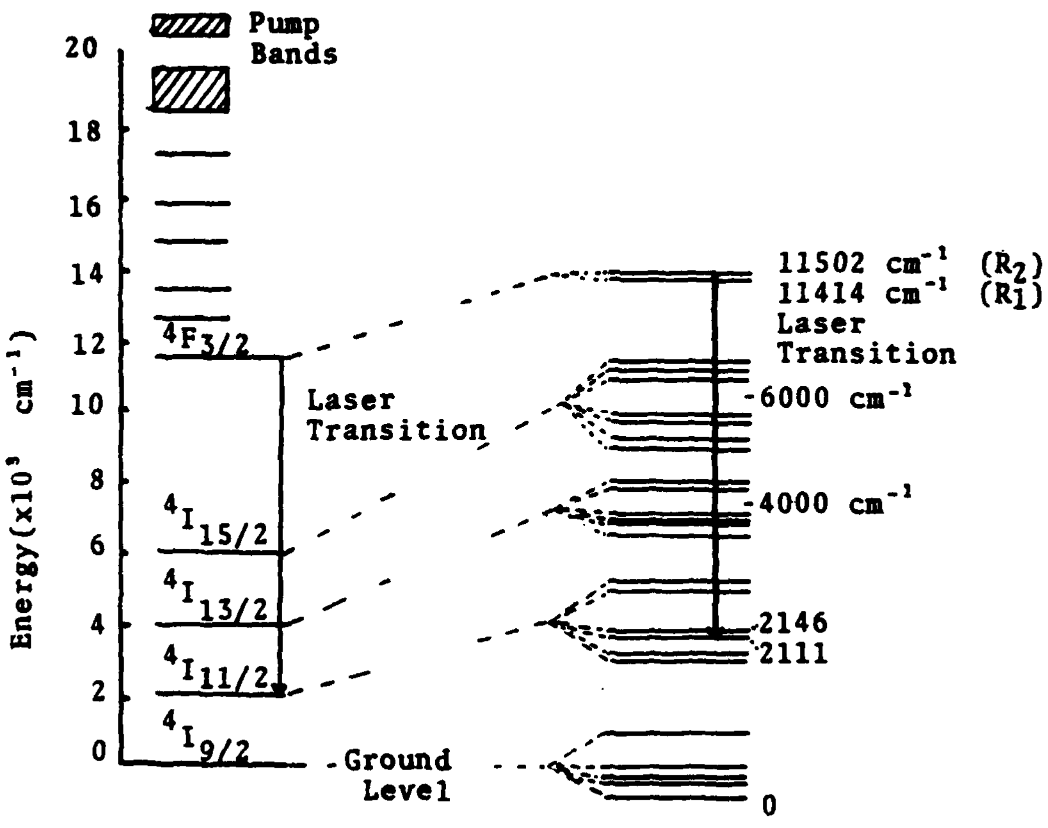


Fig. 3. Energy level diagram of Nd:YAG

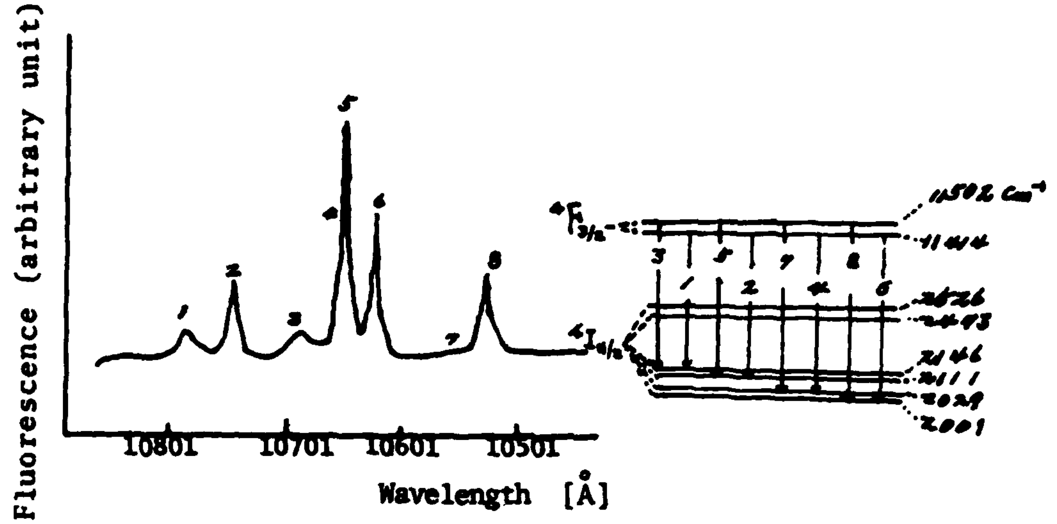


Fig. 4. Fluorescence spectrum of Nd^{3+} in YAG at 300°K in the region of 1.06μm.

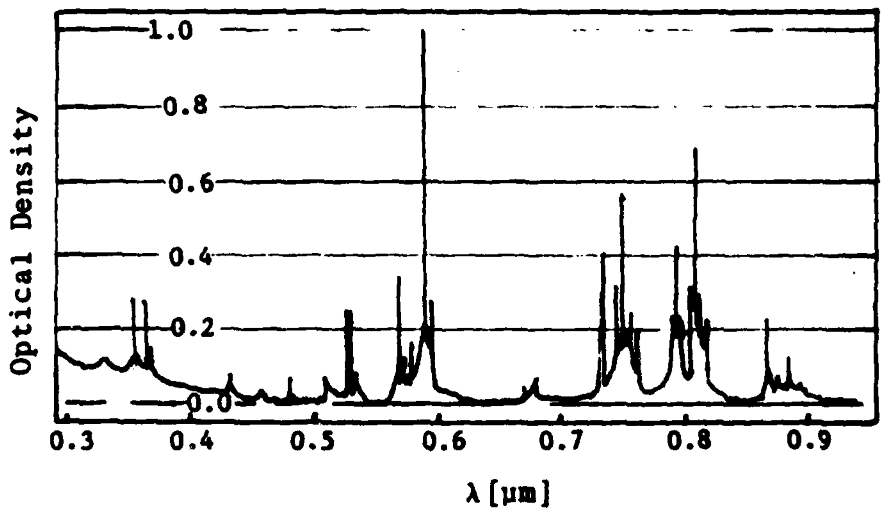


Fig. 5. Absorption spectrum of Nd:YAG at 300°K

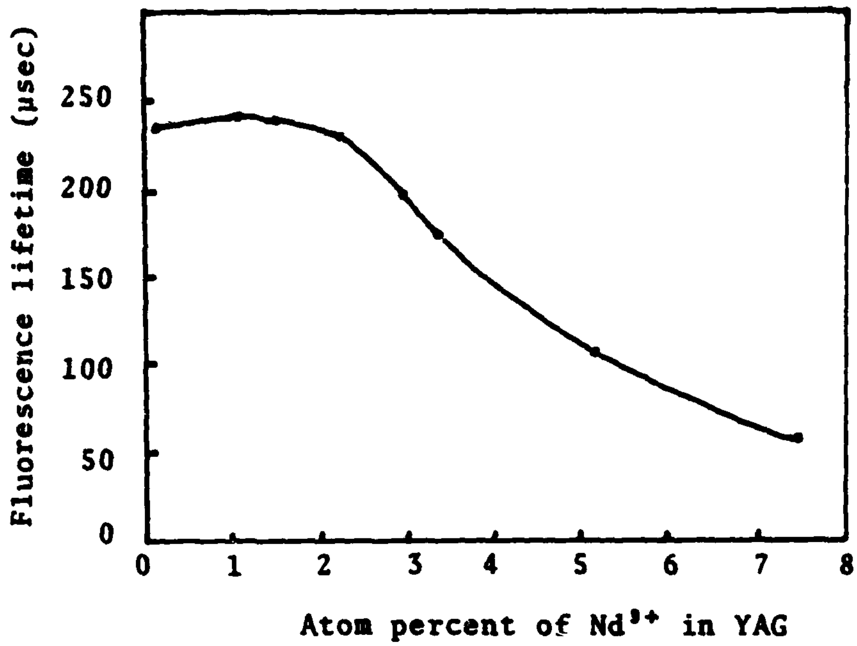


Fig. 6. The lifetime dependence of the 1.06 μm Fluorescent line in Nd:YAG with Nd^{3+} concentration

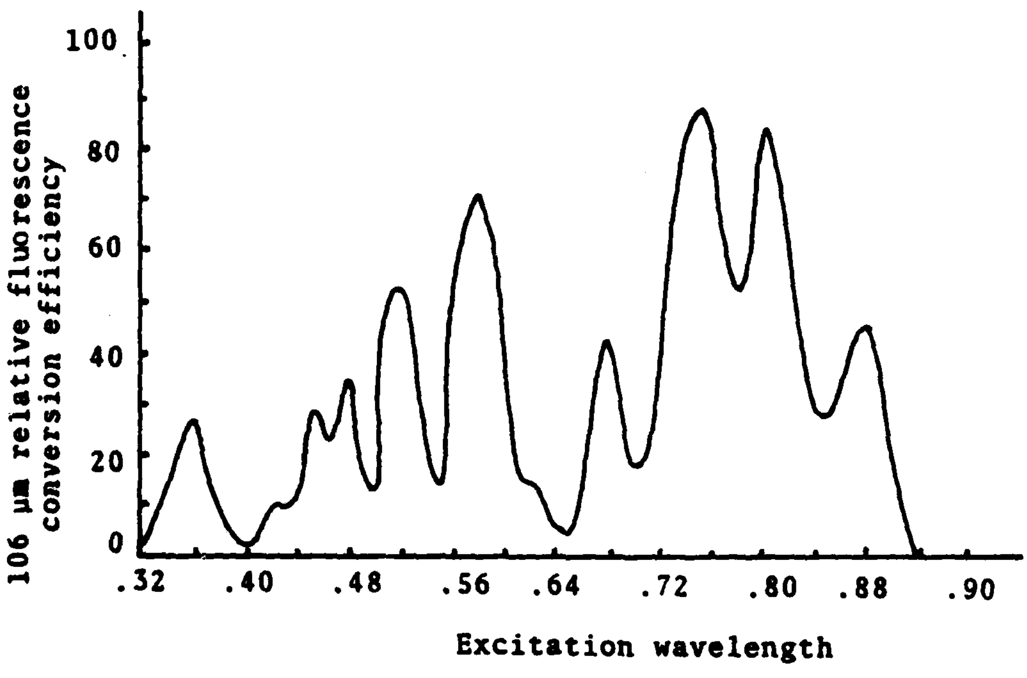


Fig. 7. Relative fluarescence conversion efficiency of Nd:YAG at 300°K

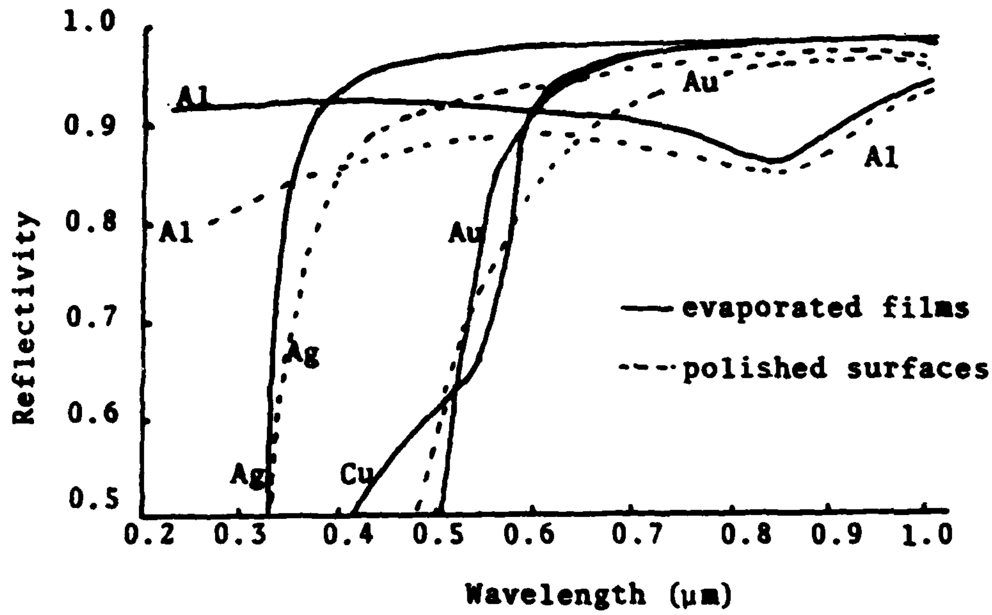


Fig. 8. Reflectivity versus wavelength for metals commonly used in the design of laser pump cavities.

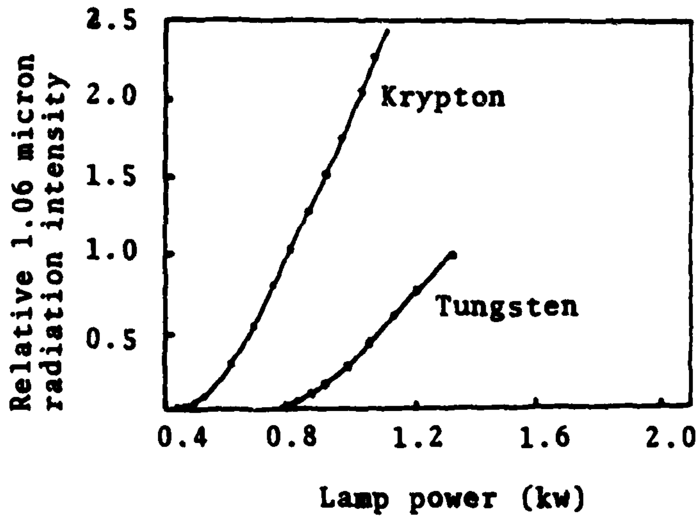
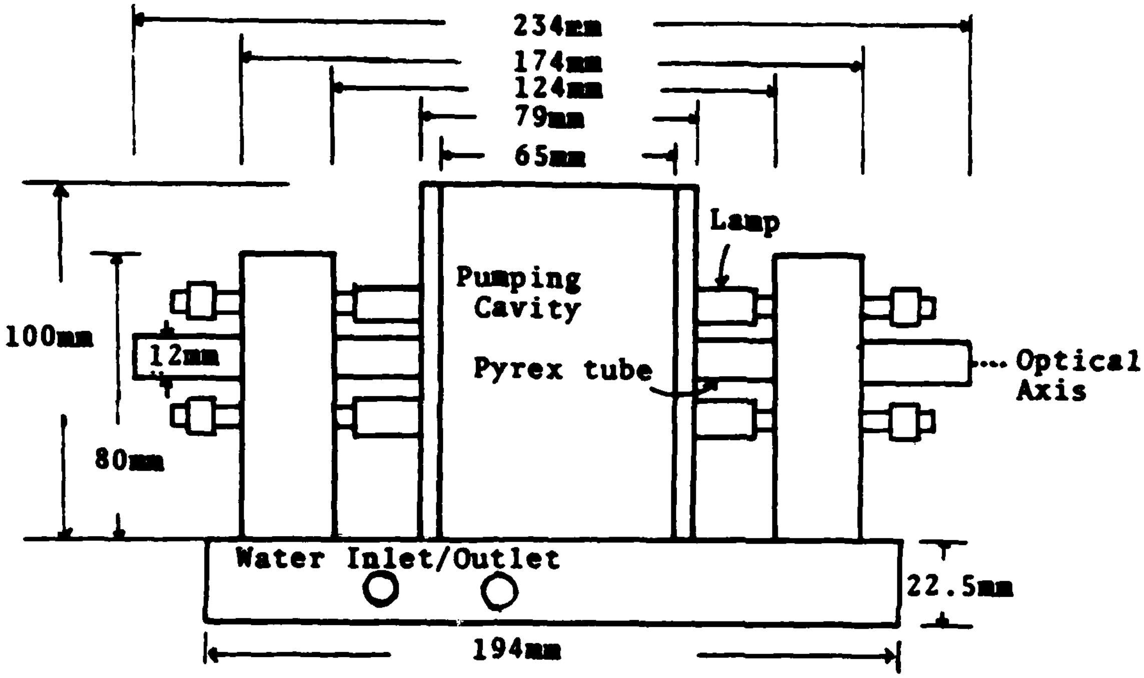
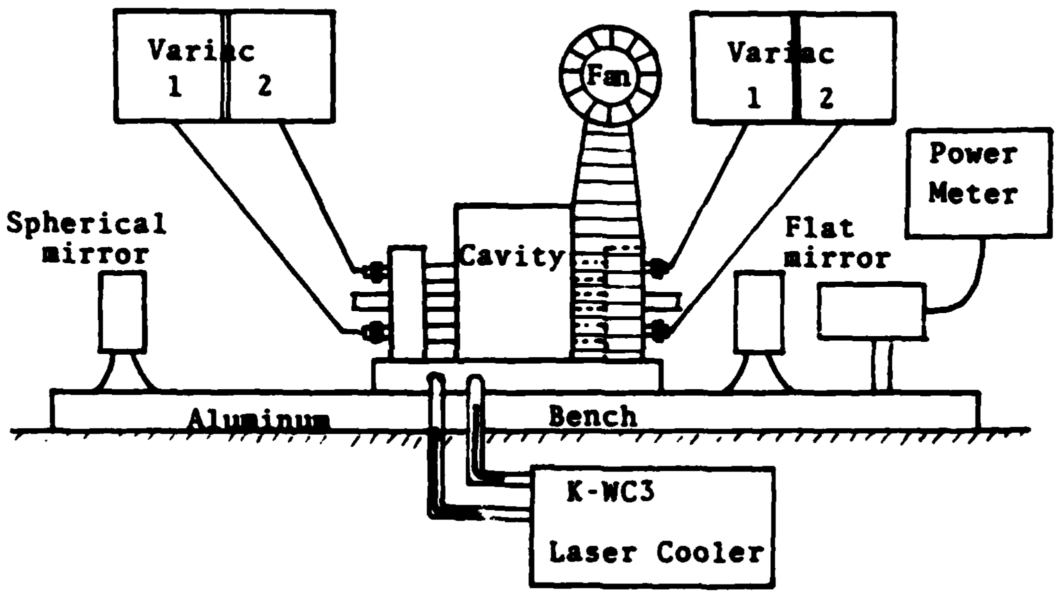


Fig. 9. Relative performance of krypton and tungsten iodine lamps for continuous pumping of YAG:Nd^{3+}.



Front view of pumping cavity scale; 2mm:1mm



Schematic sketch of the laser system

Fig. 10. General view of the Laser System

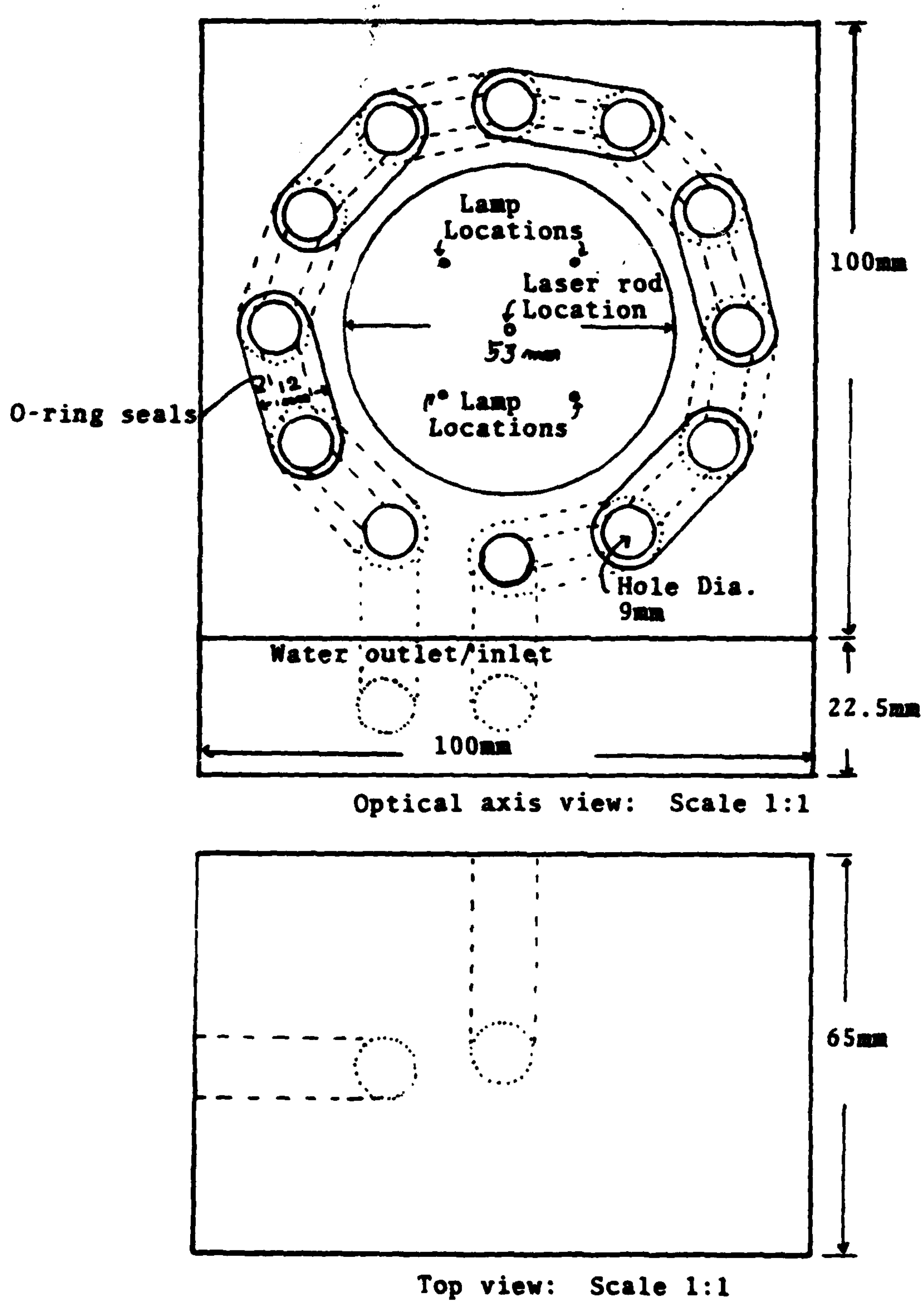


Fig. 11. Optical pumping cavity

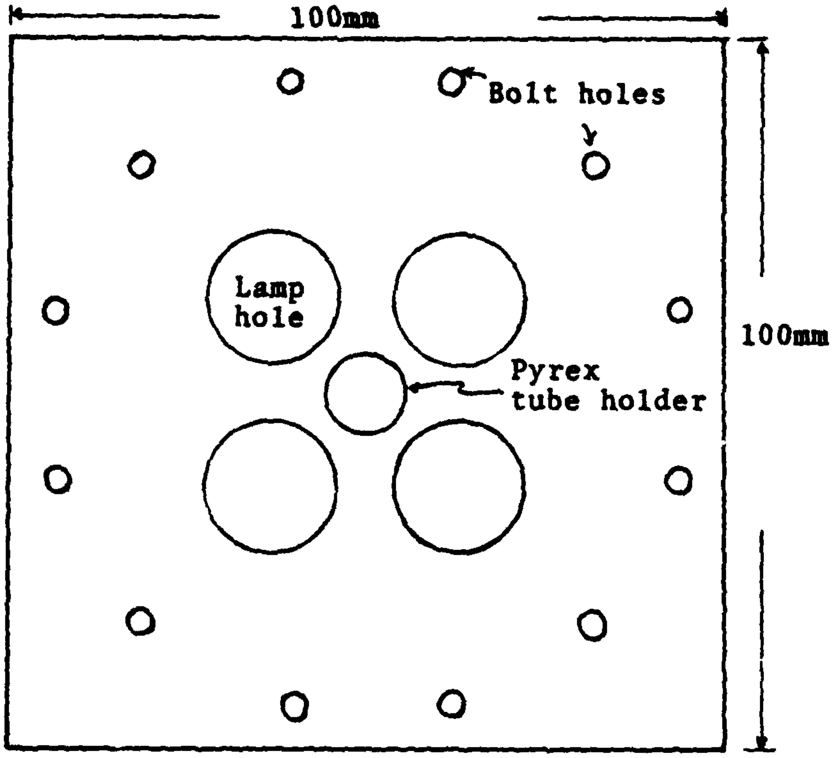
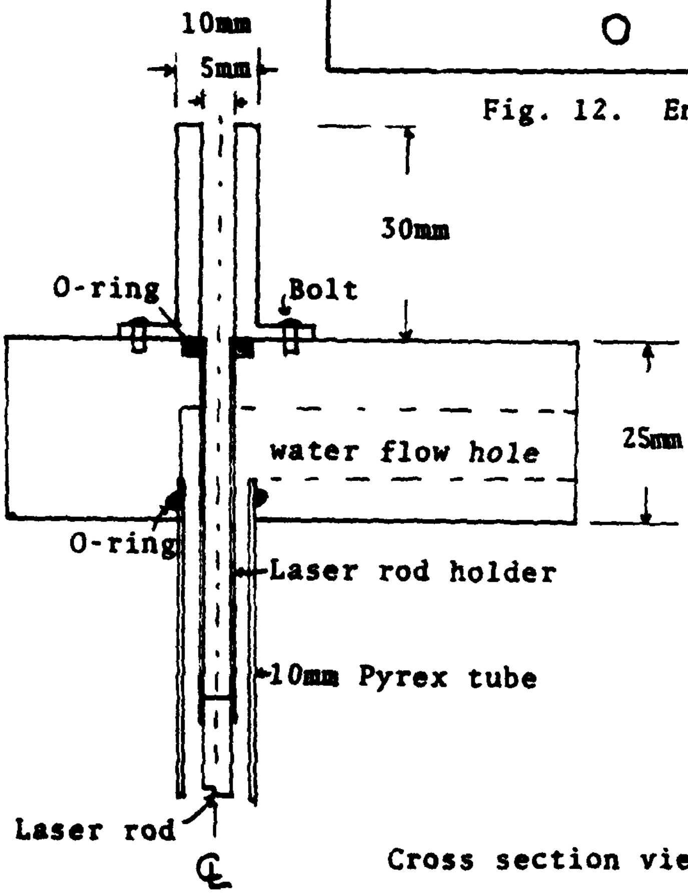
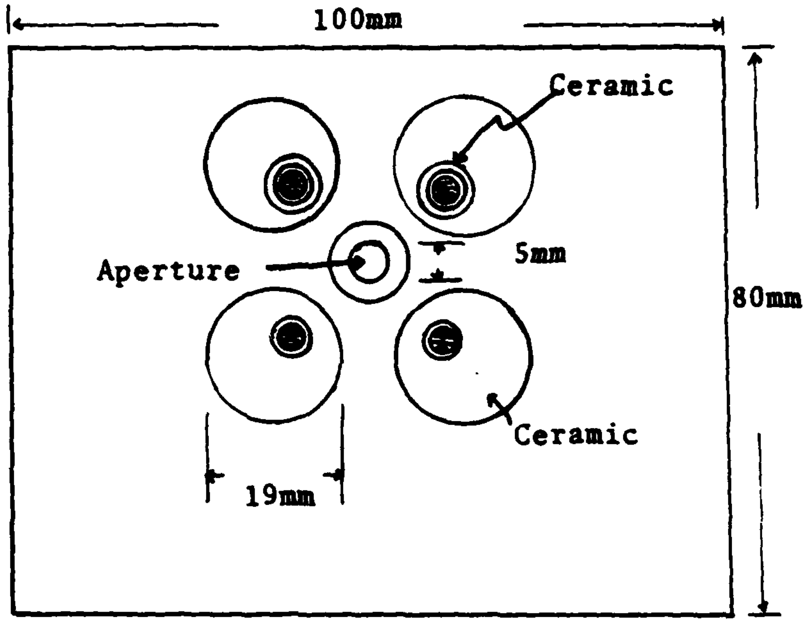


Fig. 12. End plate: Scale 1:1

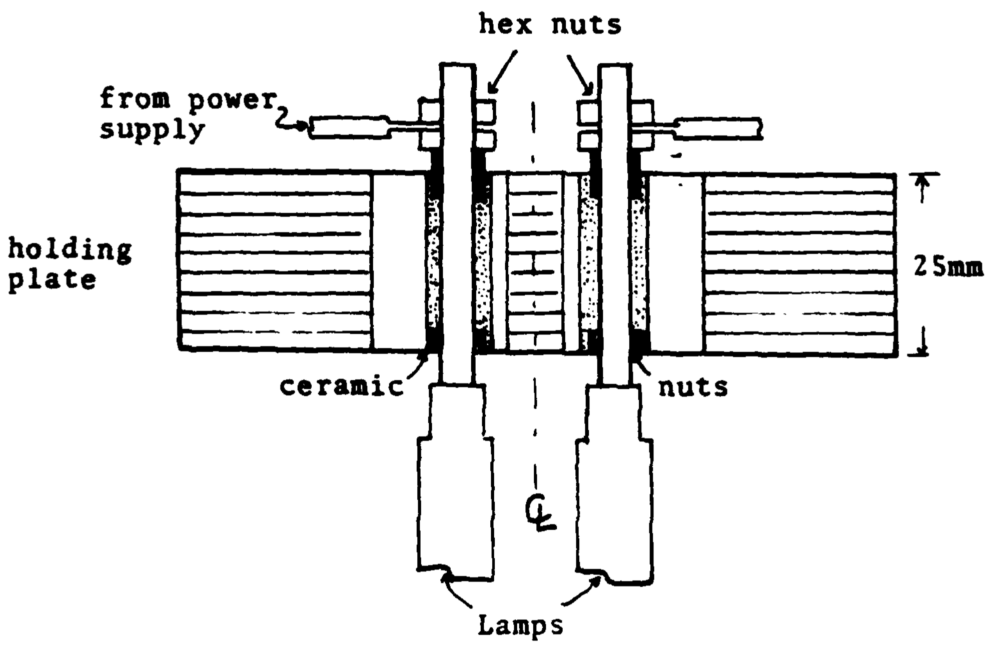


Cross section view: Scale 1:1

Fig. 13. Laser Rod Mounting Assembly



Front View: Scale 1:1



Cross section view: Scale 1:1

Fig. 14. Detail of pump lamp holding assembly

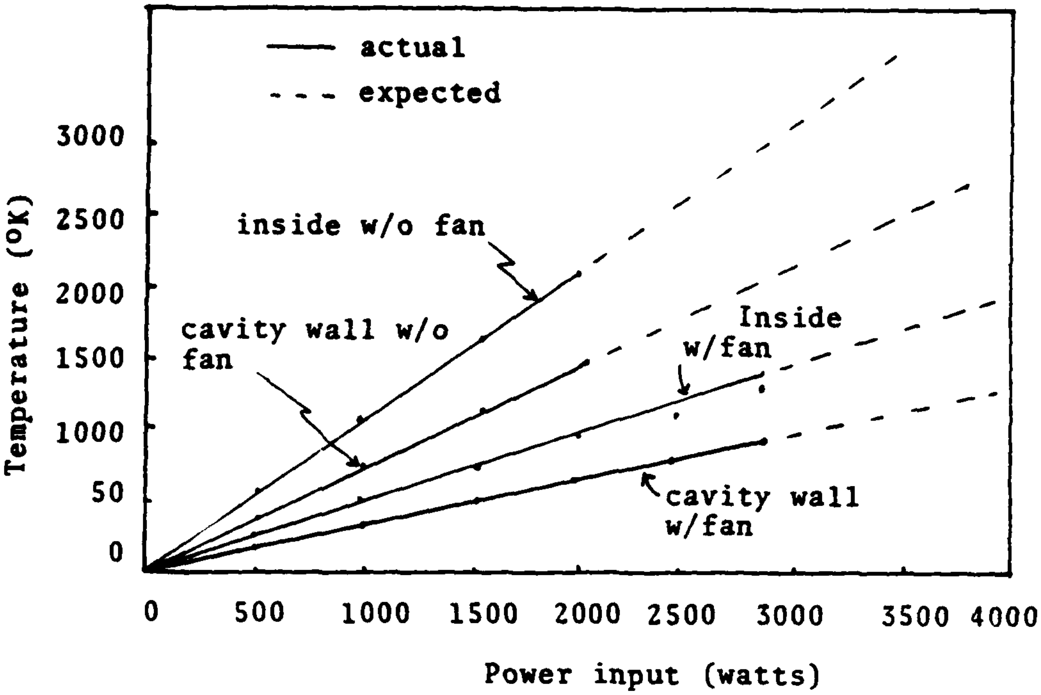


Fig. 15. The temperature inside cavity measured with fan and without fan with 100 CFM.

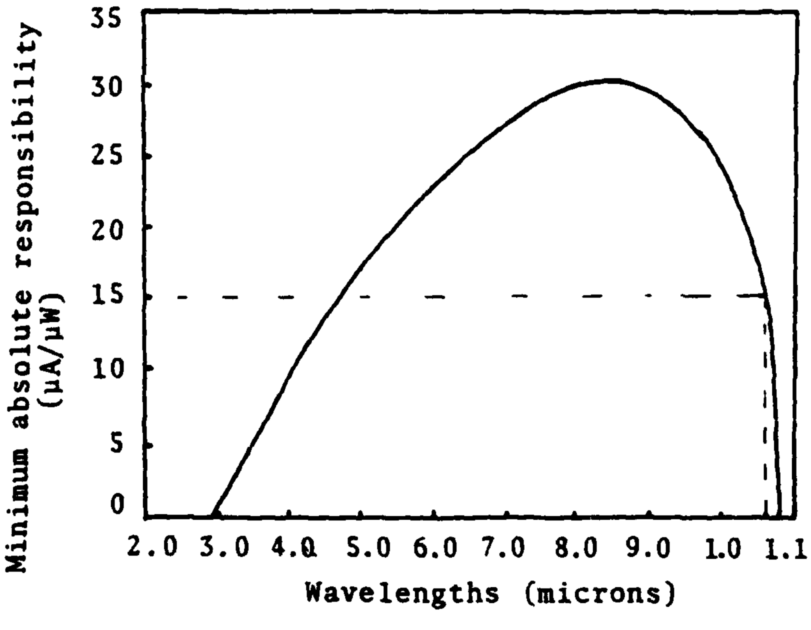


Fig. 16. The spectral response of PIN-10DP

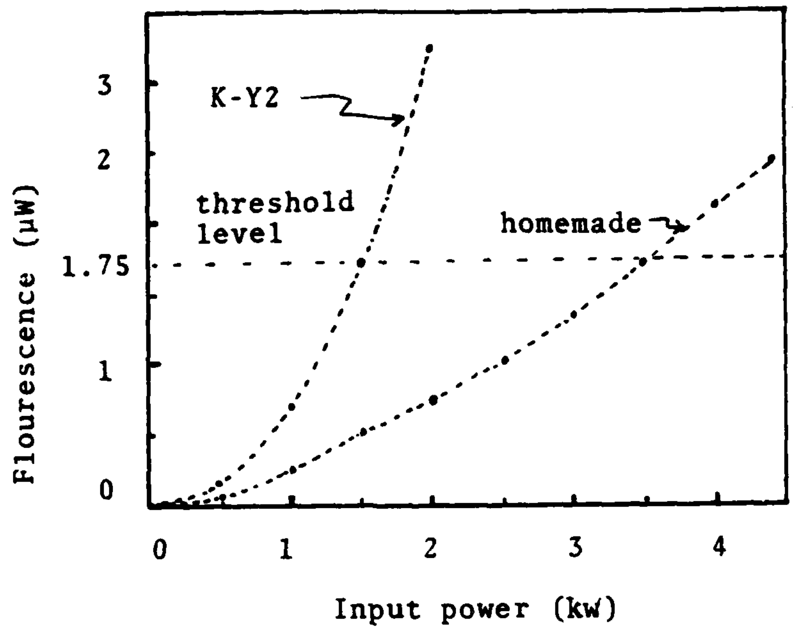


Fig. 17. Fluorescence measured from K-Y2 and homemade laser system

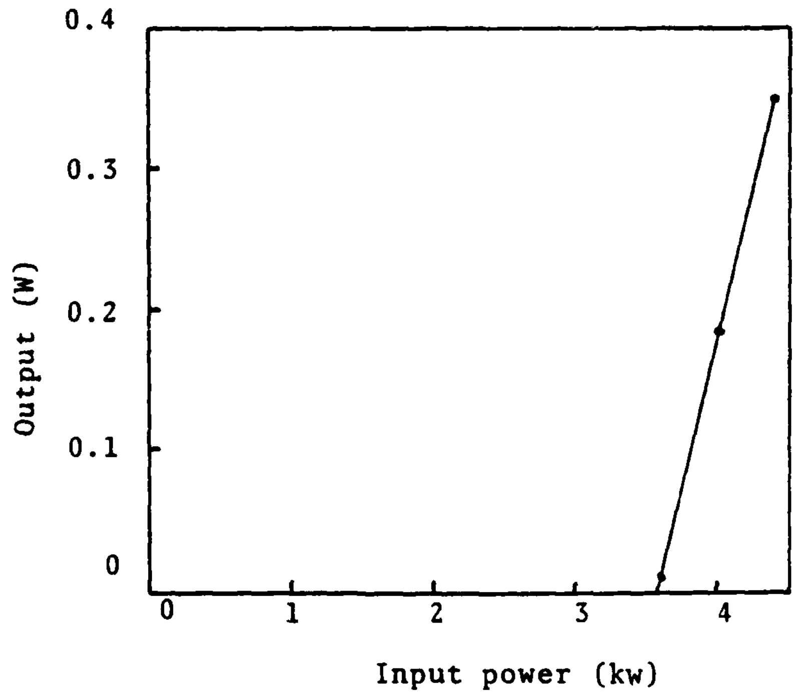


Fig. 18. Laser output of homemade system

APPENDIX A:

LOCATION OF LAMPS IN CIRCULAR CYLINDRICAL CAVITY

The circular cross section pumping cavity is approximately a "close-packed" configuration in which the pumping efficiency is dominated by the radiation directly intercepted by the rod without reflection from the cavity wall. This implies that the lamps should be located as close to the rod as is feasible, consistent with adequate cooling of the system. During tests of the cavity, comparisons were made of the fluorescent power with two lamp-rod spacings, showing 1.1 μW at 13 mm spacing compared with 1.8 μW at 9.5 mm, for 3600 watt input power. These figures are roughly consistent with an inverse square law variation with spacing.

LIST OF REFERENCES

1. O'Harrow, Patrick Ralph, The Construction of a Nd:YAG Laser to Study Atmospheric Transmission Properties, M.S. Thesis, Naval Postgraduate School, Monterey, CA December 1972.

2. Koechner, Walter, Solid-State Laser Engineering, p. 55, Springer-Verlag, New York Inc., 1976.

3. Kushida, T., and J. E. Geusic, Physics Rev. Letters, 21, 1172 (1968).

4. Levine, Albert K. and Anthony J. Demaria, Lasers, vol. 4, p. 11, (1976).

5. Kushida, T., and J. E. Geusic., Proceedings of the IEEE, October 1970.

6. Koechner, Walter, Op. Cit., p. 56.

7. Ibid., p. 57.

8. Thornton, Ronald J., et al., "Properties of Neodymium Laser Materials", Applied Optics 8 (June 1969), p. 1087.

9. Ibid., p. 1098.

10. Koechner, Walter, Op. Cit., p. 327.

11. Harry, John E., Industrial Lasers and Their Applications, McGraw-Hill Book Company (UK) Limited, 1974.

12. Kiss, Z. J. and R. J. Pressley, "Crystalline Solid Lasers", Applied Optics, vol. 5, No. 10, October 1966.

13. Koechner, Walter., Op. Cit., p. 271.

14. Read, T. B., "The CW Pumping of YAG:Nd^{3+} by Water-Cooled Krypton Arcs", Applied Physics Letters, 9., p. 343. (1 November 1966).

15. Koecher, Walter, Op. Cit., p. 59.

16. Read, T. B., Op. Cit., p. 343.

17. Koechner, Walter., Op. Cit., p. 387.

18. Fowles, Grant R., Introduction to Modern Optics, p. 274, Holt, Rinehart, and Winston, Inc., 1968.

19. Ibid., p. 276.

20. Koechner, Walter, Op. Cit., p. 87.

21. Harry, John E., Op. Cit., p. 47.

BIBLIOGRAPHY

Allen, R. B. and Scalise, S. J., "Continuous Operation of a YAlD:Nd Laser by Injection Luminescent Pumping", Appl. Physics Lett., v. 14, p. 188-190, 15 March 1969.

Amnon, Yariv. Introduction to Optical Electronics, Holt, Rinehart, and Winston, Inc., 1976.

Draegert, D. A., "Efficient Single-longitudinal Mode Nd:YAG Laser", IEEE J. Quantum Electron, v. QE-8, p. 235-239, February 1972.

Foster, J. D. and Osternik, L. M., "Thermal Effects in a Nd:YAG Laser:, J. Appl. Phys., v. 41, p. 3656-3663, August 1970.

Arecchi, F.T. and E. O. Schultz-dubois, Laser Handbook, vol. 1, North-Holland Publishing Company, Amsterdam, 1972.

Kogelnik, H. and T. Li, "Laser Beams and Resonators", Appl. Optics, v. 5, p. 1550-1557, October 1966.

Kushida, T., Marcos, H. N., and Geusic, J. E., "Laser Transition Cross Section and Fluorescence Branching Ratio for Nd^{3+} in Yttrium Aluminum Garnet", Phys. Rev., v. 267, p. 289-291, 10 March 1968.

Liberman, I. and R. L. Grassel, "A Comparison of Lamps for the Use in High Continuous Power Nd:YAG Lasers", Appl. Optics, v. 9, p. 1875-1878, September 1969.

Polloni, R. and Svelto, O., "Static and Dynamic Behavior of a Single-Mode Nd:YAG Laser", IEEE J. Quantum Electron, v. QE-4, p. 481-485, August 1968.

Smith, William V., Laser Applications, Artech House, Inc., 1976.

Yoshikawa, S., K. Iwamoto, and K. Washio "Efficient Arc Lamps for Optical Pumping Neodynium Lasers", Appl. Optics, v. 10, p. 1620-1623, July 1971.

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